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A Note of Appreciation for the MUS

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This note has been written to acknowledge the pervasive impact the Method of Universal Slopes (MUS) [1] has had on the design and development of the Space Shuttle Main Engine (SSME) through its use in material fatigue properties definition for component analysis. Included is a brief historical perspective describing propulsion system development leading up to the SSME, the need for fatigue analysis capability in the SSME design, the role that MUS played in meeting that need as a material modeling tool and the engine's subsequent successful operating history.

Rocket engines such as the Atlas, Delta, J-2 and F-1 that were designed in the 1950 to 1965 time frame were expendable engines with a single flight requirement. Those engines were designed primarily on the basis of static strength. Components were evaluated based upon their ability to sustain or survive internal or external pressure, the effects of body forces induced by high-speed rotation and external flight loads. The procedural approach for design was to supplement limited structural analysis, material failure modeling and dynamic environment definition, with extensive component and engine testing until all known hardware issues were resolved.

In contrast, the Space Shuttle Main Engine (SSME), designed in the 1970 time frame, required a fourfold increase in the energy density of its turbopumps, a three fold increase in dynamic flow loads, chamber heat flux and internal system pressures and a reuse criterion of 55 flights. It was the first rocket engine with a reusable, man-rated requirement, so it necessitated the additional consideration of detailed dynamic loads and the performance of structural response and life prediction through fatigue analysis on an overall engine basis. The amount of hardware available for development testing was significantly less than previous engines. This meant that more accurate analysis would be substituted for large scale component testing.

During the preproposal stage for this engine when the 55 flight requirement was under discussion, Rocketdyne recognized that a quantified method of calculating low cycle fatigue (LCF) lives ranging from 100 to 1000 cycles would be required. Cyclic strain ranges of 2 to 3% were projected for each engine duty cycle in critical areas of the engine where large thermal gradients and high pressures occur. Available methodologies were researched for the calculation of LCF in this extremely low life regime. Courses taught by Prof. Manson on LCF were attended by Rocketdyne personnel and a long term association was started with Prof. Manson, Gary Halford and the rest of the fatigue group at The NASA Lewis Research Center (LeRC).

A major issue with respect to LCF was property definition. Since little or no LCF data was available for potential SSME materials in the projected environments, the ability to predict fatigue properties from tensile ultimate, ductility and Young's modulus using MUS allowed the use of much simpler tests to generate LCF curves. Two classes of curves were defined: predicted curves where no fatigue or limited fatigue data was available and expected curves where sufficient fatigue test data was available to develop best fit curves.

The SSME analysis approach was to use design minimum properties from smooth specimens and local stresses and strains predicted from detail hardware analysis to calculate component damage. The information from Manson's work in [1] and [2] on comparing MUS to LCF test results for a large number of materials was used as a basis for determining a life factor of 3 for adjusting the MUS curve calculations to develop predicted minimum curves. The SSME was designed predominantly through the use of these predicted minimum curves since the design and a major part of the development effort was completed prior to the availability of confirming fatigue tests. Additional life reduction factors, such as the 10% rule [3], were utilized when high temperature effects such as creep interactions were present.

When direct material test results are available, expected minimum design curves are developed using a life reduction factor of 2 from typical in conjunction with additional data coverage criteria. Checks are also made of the design curves to insure that they are consistent with the physical metallurgical knowledge available for the particular material or material class at temperature. When the confirming fatigue tests were completed for SSME materials, very few of the predicted minimum fatigue curves had to be lowered, which confirmed the conservative nature of the implemented design approach using the MUS.

The SSME uses a variety of high strength nickel base alloys, iron based alloys, aluminum castings, titaniums and copper alloys. The environments range from temperatures of-420F to 1800F and hydrogen pressures greater than 5000 psi in major areas of the engine. The primary concern with the high pressure hydrogen environment is that it causes embrittlement in many materials that operate at room temperature during plastic straining of the material. The MUS was utilized by Rocketdyne for the full gamut of environments and engine conditions listed above.
The actual engine use based on the design analysis criteria and the MUS based properties resulted in minimal engine problems attributable to these methodologies. The MUS based design methodology was instrumental to the successful design and development of the SSME and crucial to the production of a highly reliable propulsion system meeting imposed time and cost constraints.

Ref.
1)Manson, S. S., "Fatigue: A Complex Subject - Some Simple Approximations", Experimental Mechanics,p. 193-226, (July 1965)
2). Manson, S .S., Thermal Stress and Low-Cycle Fatigue, McGraw Hill, (1966)
3. Manson, S. S., "Interfaces Between Fatigue, Creep and Fracture," International Journal of Fracture Mechanics, Vol. 2, No. 1, p. 327-363, 1966.

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